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INTERPRETATION OF RAPID RISES IN HARD X RAYS AND MICROWAVES WITH THE THERMAL CONDUCTION FRONT MODEL

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ABSTRACT

Impulsive hard X-ray and microwave bursts with rise times from 0.1 to 10 seconds are discussed. Source areas calculated by the method of Crannell et al. (1978) were compared with source areas determined from Hinotori and HXIS images. The agreement strongly suggests that the method is valid. If the thermal conduction front model for the hard X-ray and microwave source is adopted, then the method enables one to derive area, density, magnetic field, and rise time from hard X-ray and microwave spectral observations. This approach was used to derive these parameters for several rapid impulsive rises in the flares of 1980 July 1 and 1984 May 21. It is shown that the model provides a consistent interpretation of the observations of these impulsive increases. Indeed, the model provides a way to calculate rise times from spectra alone (to within a factor of about three) over more than two orders of magnitude.

1. INTRODUCTION

This paper has two purposes. First, we evaluate a method first applied by Crannell et al. (1978) to calculate the area of a flare source of hard X rays and microwaves from data without spatial resolution. The area calculation is made by assuming that a single thermal distribution of energetic electrons emits the microwaves (thermal gyrosynchrotron radiation) and the hard X rays (thermal bremsstrahlung). We show that the method yields values in agreement with those observed with spatially resolved hard X-ray imaging instruments for the two test cases considered. With this additional support for the method, we go on to apply it to some rapid spike bursts and show that the thermal conduction-front model fits the rise times of the rapid bursts. The rapid bursts have rise times from 0.1 to 1.4 s, and allow us to extend the thermal analysis to bursts almost 10 times more rapid than heretofore. The thermal analysis of these bursts suggests that they occur in smaller coronal loops with unusually high magnetic fields, but represent part of a continuous family of impulsive bursts with rise times as long as 20 sec, studied previously (Crannell et al. 1978; Batchelor 1984; Batchelor et al. 1985). At present, nonthermal models of flare hard X-ray and microwave bursts do not make specific analogous predictions that can be compared with the results of the thermal analysis. Such predictions are sorely needed to make a meaningful comparison possible.

2. REVIEW OF AREA CALCULATION

The area of a hard X-ray and microwave burst source was calculated from the Rayleigh-Jeans law:

$$S(f) = 1.36 \times 10^{-44} f^2 A_0 T_e \quad (1)$$

where S is the microwave flux (solar flux units -- 1 sfu = 10^{-22} W m^{-2} Hz^{-1} at a frequency f (Hz) in the optically thick portion of the microwave spectrum, A_0 is the area (cm^2), and T_e is the temperature (deg K) found by spectral fit to the hard X-ray spectrum. The units are those of Batchelor et al.; Crannell et al. expressed the temperature in keV.

Equation (1) is strictly applicable only to a homogeneous thermal source. There is evidence that variations in temperature and magnetic field sometimes affect the spectra (Matzler 1978; Schochlin and Magun 1979; Dulk and Dennis 1982). For the optically thick part of the microwave spectrum of interest here, the result of these nonuniformities is to alter the index of f in Equation (1) to a value less than 2. Considerations of a suitable model for such a nonuniform thermal source lead to the conclusion that the central, hottest part of the source is the origin of the optically thick emission of maximum frequency. The most intense X-ray emission also would originate in the hottest region of the source. Thus, if the index of the optically thick microwave emission is less than 2, then the area can be approximated by using the flux at the maximum frequency of optically thick emission in Equation (1).

3. TEST OF AREA CALCULATION

Two sources of data currently can be used to test the derivation of hard X-ray area: the Hard X-ray Imaging Spectrometer (HXIS) aboard SMM, and the two Solar X-ray Telescope (SXT) instruments aboard the Japanese Hinotori spacecraft. SXT data for one flare have been used by Wiehl et al. (1985), but no HXIS area has been compared with the area of the same flare calculated by this method. In addition, microwave observations from Bern and Sagamore Hill were available for these tests.

Test case 1: Hinotori SXT Observation

Wiehl et al. made use of the image of the 1981 August 10 flare at 0659:06 UT, published by Ohki et al. (1982). This is shown in Figure 1 (a). The area enclosed in the 40% peak contour is 1.2×10^{18} cm^2. The temperature was found by Wiehl et al. to be 3.1×10^8K, by means of a thermal bremsstrahlung function fit to the 30-500 keV spectrum from the Hard X-Ray Burst Spectrometer (HXRBS) on SMM. Microwave spectra from Bern were available. The area calculated from Equation (1), using a microwave flux of 779 sfu at 11.8 GHz, is 1.3×10^{18} cm^2.

Test case 2: HXIS Observation

In Figure 1 (b), the raw image data are shown for the 1980 May 21 flare during the sharpest, largest rise in hard X rays. If we choose the 40% contour again, for consistency, 18 pixels are at the 40% level, yielding a total area of 5.6×10^{18} cm^2. The spectrum of microwaves was observed at Sagamore Hill. Optically thick emission at 4.995 GHz was observed of approximately 1200 sfu. The temperature from the HXRBS fit was 6.6×10^8K. The calculated area is 5.4×10^{18} cm^2.

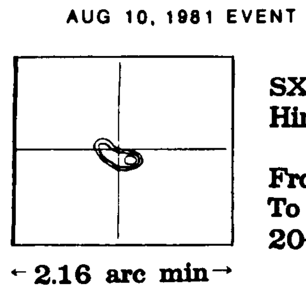
The close numerical agreement between measured and model-derived area in each case is within the uncertainties, which were estimated to be a factor of about three (Batchelor et al.).

4. THE THERMAL CONDUCTION-FRONT MODEL AND THE DERIVED AREA

A thermal model for the production of hard X rays in impulsive flares was originally proposed because the popular nonthermal models required intense beams of electrons with embarrassingly large number densities and energies to explain the observed hard X-ray fluxes from flares (e.g. Hoyng, Brown, and van Beek 1976). Whereas bremsstrahlung of a nonthermal beam in a thick target is a very inefficient process, emitting only about 10^{-5} of the electron energy as X rays, thermal bremsstrahlung from a confined, thermally relaxed electron distribution offered a much more efficient mechanism to produce the radiation,

TEST OF AREA CALCULATION

Case 1



SXT1 Hard X-ray Image
Hinotori Spacecraft

From 0658:55.200 UT
To 0659: 1.876 UT
20-40 keV

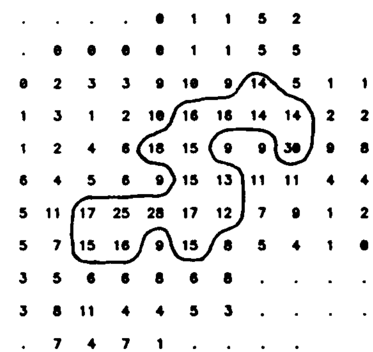
Contours: 80%, 60%, 40%
(Ohki et al. 1982)

Measured area within 40% contour: 1.2 x 10^{18} cm^2

Calculated area (779 sfu @ 11.8 GHz): 1.3 x 10^{18} cm^2
(Wiehl et al. 1985)

Case 2

HXIS, SMM Spacecraft
May 21, 1980



From 2055:44 UT
To 2055:54.5 UT

8 arc sec per pixel
16-30 keV

18 pixels › 40% of maximum: 5.6 x 10^{18} cm^2

Calculated area (1200 sfu @ 5 GHz): 5.4 x 10^{18} cm^2

Figure 1. Comparison between area of X-ray source within 40% contour and derived source area for two flares. Solar north is up.

if the confinement was sufficiently good. Brown, Melrose and Spicer (1979) introduced the idea that an impulsively heated electron population at the top of a coronal loop might be confined by ion-acoustic turbulence excited by electrons attempting to escape from the source. Smith and Lilliequist (1979) explored this model with fluid simulations, and this led to a number of papers by Smith and collaborators in which the model was refined. Many variations on the thermal conduction-front model have since appeared in the literature. Batchelor et al. (1985) gave arguments for the confinement of high-energy microwave-emitting electrons in the source as well. A schematic of that variation of the model appears in Figure 2.

It is assumed that heating of the electrons near the apex of a loop is continuous until the peak of the hard X-ray burst or later. This is the assumption of Smith and collaborators rather than Brown, Melrose and Spicer, who assumed impulsive heating and studied the aftermath. Observational evidence for this assumption comes from the time histories of fitted temperature during the rises of bursts, which typically indicate rising temperature. The theoretical arguments of Batchelor et al. suggest that the microwave and hard X-ray-emitting regions are cospatial up to the peak of the burst. It is justified then to use the area derivation described in Section 2 to estimate the loop length. If Equation (1) is used to derive A_0, then the half-length of the loop is proportional to $L_0 = A_0^{1/2}$.

In the continuous heating version of the model considered here, the rise time of the hard X rays is then the travel time of the conduction front from the loop apex to the chromosphere. The velocity of the conduction front is approximately $c_s = (kT_e/m_p)^{1/2}$, the ion-acoustic velocity. T_e is found from the hard X-ray thermal bremsstrahlung spectral fit. Therefore the rise time of an impulsive burst in this variation of the model is $L_0/c_s = \tau_0$. If the assumptions of the model are valid, we should find t_r, the rise time measured from the time history of a spike burst, to be linearly related to τ_0, which depends on spectral parameters only. This linear relation was found to hold by Batchelor et al. for the set of 20 impulsive rises from different flares with rise times ranging from 1.8 to 22 s.

The impulsive and continuous-heating versions of the model have been studied analytically by MacKinnon (1985). That work supports our assumption, $t_r = L_o/c_s$, given that heating continues for $t \geq t_r$ after the start of the burst.

We proceed to test this prediction of the thermal conduction-front model with data from additional rapid rises from two flares.

5. RAPID RISES IN THE 1980 JULY 1 FLARE

The flare produced a series of seven sharp peaks, superposed on a more gradual component, which we treat as background. These peaks are shown in

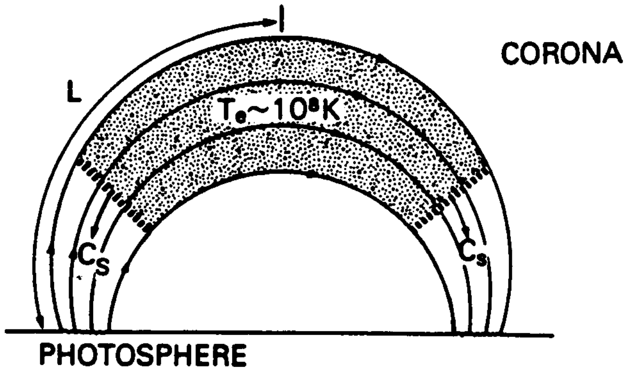


Figure 2. Schematic of the conduction-front model for emission of impulsive hard X rays (30-500 keV) and associated microwaves.

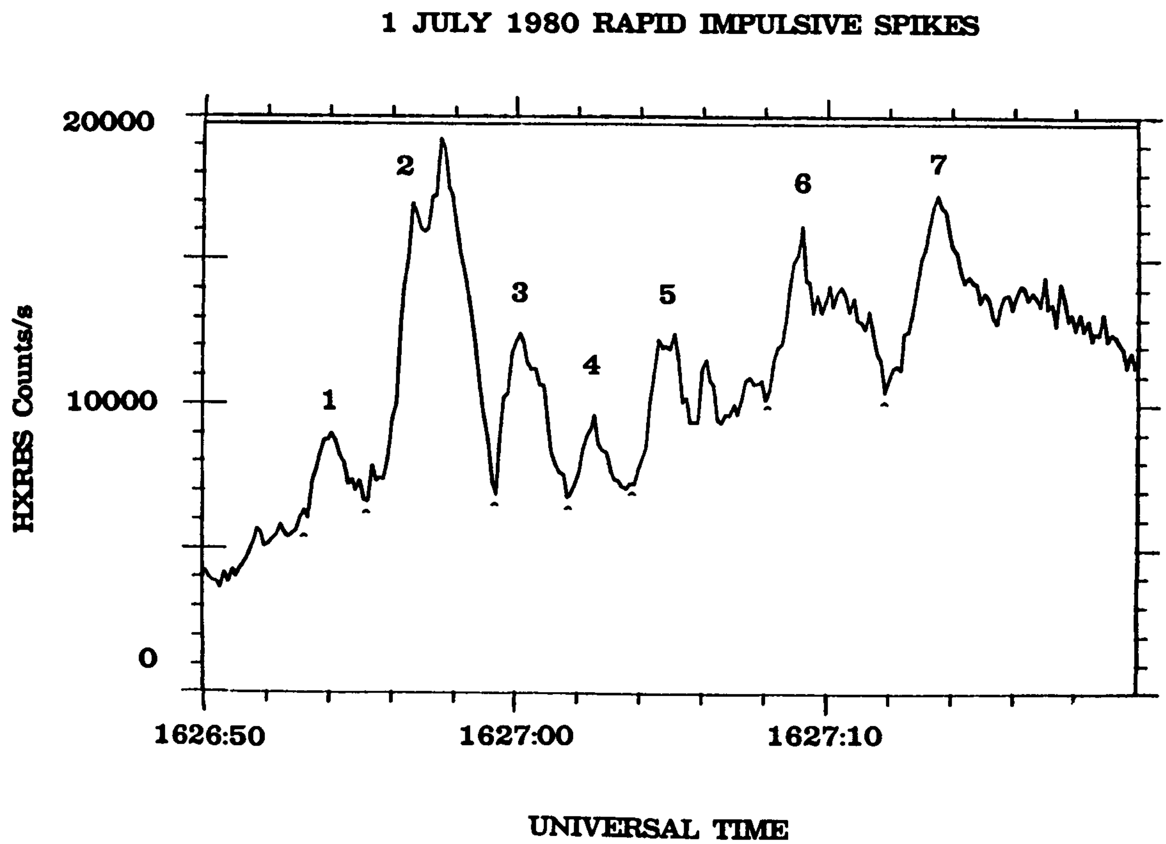


Figure 3. Time-intensity plot of the seven rapid impulsive rises in hard X rays (33-490 keV) on 1980 July 1, observed with HXRBS.

X rays in Figure 3. Microwave data were also available from Bern, courtesy of A. Magun.

Hard X-ray spectra of the seven spikes were computed by fitting a thermal bremsstrahlung function as described in Batchelor et al. Microwave fluxes were computed at the maximum optically thick frequency. The observed and derived parameters for these spikes appear in Table 1. The table includes several parameters of interest that are defined by formulae in Batchelor et al. The emission measure ($n_e^2 L_0^3$) and temperature of the fitted thermal bremsstrahlung function are listed, μ and T_e. The observed rise time, t_r, and the predicted rise time, τ_0, computed from S, f, and T_e, are in neighboring columns. The magnetic field is calculated from our estimate of the peak frequency of the microwave spectrum, f, and from S, T_e, and μ (see Equation (15) of Batchelor et al.). The formula is derived from the simplified expressions for gyrosynchrotron emission by Dulk and Marsh (1982). The electron density, n_e, and thermal energy density, w_T, are derived from μ and L_0. The standard plasma β for the electrons is also given. The < and > symbols with some values of B and β occur because f is a lower bound on the microwave peak frequency.

Table 1
Observed and Derived Parameters for 1980 July 1 Spikes

No.	Observed					Derived from Model					
	μ	T_e	S	f	t_r	τ_0	L_0	B	n_e	w_T	β
	10^{45} cm^{-3}	10^8K	sfu	GHz	s	s	10^9 cm	gauss	10^9 cm^{-3}	erg cm^{-3}	
1	.36	4.9	135	19.6	.8	1.1	.22	325	5.7	580	.14
2	1.0	6.4	750	35	.9	1.1	.26	>470	7.4	980	<.11
3	.53	5.7	39	19.6	.8	.53	.11	270	19	2200	.77
4	.22	6.5	82	35	1.0	.4	.086	>470	19	2600	<.29
5	.40	7.1	486	28	.8	1.0	.25	350	5.0	730	.15
6	.43	7.3	894	35	1.0	1.1	.27	>440	4.5	680	<.088
7	.44	7.8	1330	35	1.4	1.3	.32	>425	3.7	600	<.083

The seven pairs of t_r and τ_0 are plotted in Figure 4, with the other pairs calculated by Batchelor et al. (Spike 2 was included in previous work; the six new values are indicated by diamond symbols.)

Noteworthy features of the parameters are the relatively high temperatures, magnetic fields and densities, as compared with the set of rises

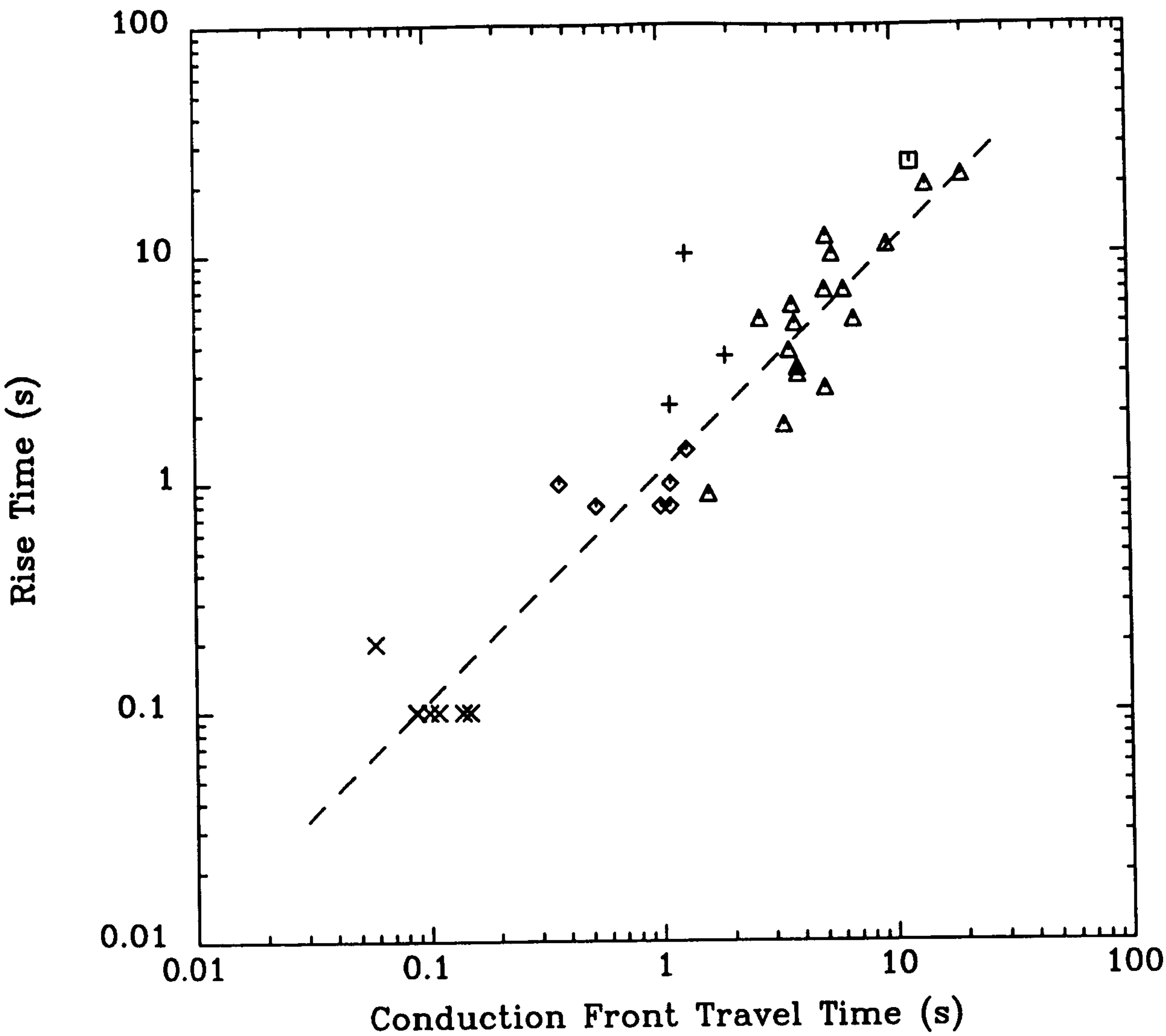


Figure 4. Correlation of measured rise times of 34 impulsive rises with rise times derived from the X-ray and microwave spectra, using the conduction front model. Triangles: rises from different flares on the disk (Batchelor et al.); pluses: rises from different flares on the limb (Batchelor et al.); square: 1980 November 5, 2232 UT; diamonds: other impulsive rises from 1980 July 1 flare; crosses: other impulsive rises from 1984 May 21 flare. The square, diamonds and crosses are presented here for the first time. The dashed line is the linear least-squares best fit to the (log t_r, log τ_o) pairs, excluding limb events because of possible occultation: $t_r = 1.12\ \tau_o^{1.00}$, correlation coefficient r = 0.96.

studied by Batchelor et al. Association of high temperatures with high fields is quite reasonable if the source of energy is magnetic reconnection. The derived loop lengths are relatively small, which is interesting because the flare was remarkably compact in Hα. The high densities might be expected in relatively small, low-lying coronal loops.

6. RAPID RISES IN THE 1984 MAY 21 FLARE

Microwave and hard X-ray data on this event were first presented by Kaufmann et al. (1985). This flare is discussed in detail by Correia et al., elsewhere in this volume. Several rapid rises in microwave flux at 90 GHz were observed, with t_r from 0.1 to 0.2 s. Seven clearly-resolved spike features from the microwave bursts labeled B, C, and E (see Correia et al.) were selected for analysis. In the simultaneous X-ray observations with HXRBS, the time resolution (128 ms) did not permit complete resolution of the spikes. The X-ray bremsstrahlung spectral fit was necessarily performed on a blend of the first three spikes in feature C and on a blend of the first three spikes in feature E. Feature B was resolved in both data sets. As in previous cases, the slow component of emission was treated as background.

The observed and derived parameters for these seven spikes are given in Table 2.

Table 2
Observed and Derived Parameters for 1984 May 21 Spikes

	Observed				Derived from Model					
Label	μ 10^{45}cm^{-3}	T_e 10^8K	S sfu	t_r s	τ_0 s	L_0 10^9cm	B gauss	n_e 10^9cm^{-3}	w_T erg cm^{-3}	β
B	0.12	7.9	20	0.2	0.059	0.015	$\gtrsim$ 940	180	29000	$\lesssim$ 0.84
C_1	0.13	7.5	40	0.1	0.088	0.022	$\gtrsim$ 990	110	17000	$\lesssim$ 0.44
C_2	0.13	7.5	55	0.1	0.10	0.026	$\gtrsim$ 1000	87	14000	$\lesssim$ 0.34
C_3	0.13	7.5	60	0.1	0.11	0.027	$\gtrsim$ 1000	81	13000	$\lesssim$ 0.32
E_1	0.32	4.5	15	0.1	0.090	0.017	$\gtrsim$ 1400	250	23000	$\lesssim$ 0.30
E_2	0.32	4.5	35	0.1	0.14	0.027	$\gtrsim$ 1400	130	12000	$\lesssim$ 0.16
E_3	0.32	4.5	40	0.1	0.15	0.028	$\gtrsim$ 1400	120	11000	$\lesssim$ 0.14

All derived values for this flare depend on observations at 90 GHz. Because of the positive spectral index in each case from 30 GHz to 90 GHz, it has been assumed that at 90 GHz the source is optically thick. The magnetic field computations are lower limits, depending on the assumption that the gyrosynchrotron spectral peak is > 90 GHz. More observations in this microwave spectral range would help to determine the properties of these rapid spikes more decisively. Values of t_r were found by measuring the time-intensity plots of microwaves given by Correia et al.

The pairs t_r and τ_0 corresponding to these seven spikes are plotted in Figure 4 as "x" symbols. The values of τ_0 should be regarded as uncertain by a factor of about three, due to blending of spikes in the X-ray spectral analysis. Nevertheless, agreement with the linear relation found in the other cases is the result. The best linear least-squares fit is $t_r = 1.12\ \tau_o^{1.00}$, with a correlation coefficient r = 0.96. (The three limb flares were omitted from correlation analysis, due to the possibility of occultation effects.)

Unusually high values of B, 10^3 gauss and more, are derived for these spikes. Loop sizes of a few hundred km, and densities of order $10^{11}cm^{-3}$ are also implied. All of these properties are consistent with an origin of the radiations in unusually low-lying magnetic loops.

Considering all of the impulsive rises analyzed here and by Batchelor et al., we find sources sizes rangeing from 150 km to 27000 km, magnetic fields ranging from 110 gauss to more than 1400 gauss, and densities ranging from $10^8 cm^{-3}$ to $2.5 \times 10^{11} cm^{-3}$. In all cases, $\beta < 1$ is found, indicating confinement of the plasma by the magnetic field, and that only a fraction of the field had to be annihilated to supply the thermal energy of the plasma. This is unlikely to result by chance alone, given the large range of parameters contributing to β, and suggests that the derived parameters are physically meaningful.

7. CONCLUSIONS

The two test cases suggest that the area computation using Equation (1) is physically meaningful. The analysis of rapid rises in the 1980 July 1 and 1984 May 21 flares leads to derived physical parameters that are reasonable for a simple extension of the same thermal source confinement mechanism to smaller loops with higher magnetic fields than usual. The linear relationship of observed and model derived rise times found by Batchelor et al. is supported for short rise times.

It bears repeating here that the linear relationship displayed in Figure 4 is not due to a strong correlation with t_r of any one of the parameters S, f, and T, that are used to compute τ_o. As shown by Batchelor et al., t_r is not correlated with either S, f, or T alone; only the combination of these parameters to compute L_o or τ_o is correlated with t_r, consistent with the model.

This thermal model provides a physically meaningful way of connecting independent temporal and spectral parameters of impulsive hard X rays and microwaves. A challenge for future work is to develop comparable nonthermal mechanisms to explain the relationship of the observed parameters in the context of a nonthermal model.

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